Importance of Engineering Equivalence in AM Materials for Certification

Douglas N. Wells
NASA Marshall Space Flight Center
Douglas.N.Wells@nasa.gov

March 3, 2022

ADDITIVE MANUFACTURING
STRATEGIES
March 1-3, 2022

New York

Presenter Biography

Douglas N. Wells

Mr. Douglas Wells is a structural materials engineer in the Materials and Processes Laboratory at the NASA Marshall Space Flight Center and serves as a deputy Technical Fellow for Materials for the NASA Engineering and Safety Center. Doug has thirty years of experience in fatigue, damage tolerance, and fracture control of flight structures. For the past nine years, he has focused on developing methodologies for the qualification and certification of additively manufactured spaceflight hardware, including the development of the NASA standards that establish requirements for incorporating additively manufactured hardware into flight vehicles for NASA and its commercial partners. In addition to standards development for NASA, Doug is actively engaged with the broader international standards community working in additive manufacturing, including ASTM and SAE. Currently, much of his time is spent on the interpretation of certification requirements for additively manufactured hardware on a variety of NASA missions. Doug came to NASA following his Bachelor of Science degree in Aerospace Engineering at Virginia Tech and also holds a Master of Science in Mechanical Engineering from Stanford University.

Presentation Outline

Topics:

1. **What is Engineering Equivalence?**
2. **Equivalence Baselines**
3. **Prerequisites for Engineering Equivalence**
4. **The Engineering Equivalence Toolbox**
5. **Applications of Engineering Equivalence**
6. **Summary and Conclusions**

What is Engineering Equivalence?

Engineering Equivalence

- Engineering equivalence is a methodology for evaluating the quality of AM materials that acknowledges the broad range of characteristics that must be assured for an alloy to meet all its expectations.
- Engineering equivalence as a concept differs from the determination of statistical equivalence for a material characteristic (such as ultimate strength) in that we determine equivalence holistically through engineering judgement by considering many interrelated and causal material characteristics as they contribute to the overall performance of the material
  - Often equivalence determinations must be made in the absence of statistically significant pools of data
- Engineering equivalence is the enabler that allows the AM material ecosystem to remain healthy and self-consistent in the face of sensitive processes with a multitude of known and unknown failure modes.
- Engineering equivalence is not an easy task - it requires reliable and diverse datasets, depth of knowledge in materials, good engineering judgement, and collaboration between engineering and quality assurance organizations.

What is Engineering Equivalence?

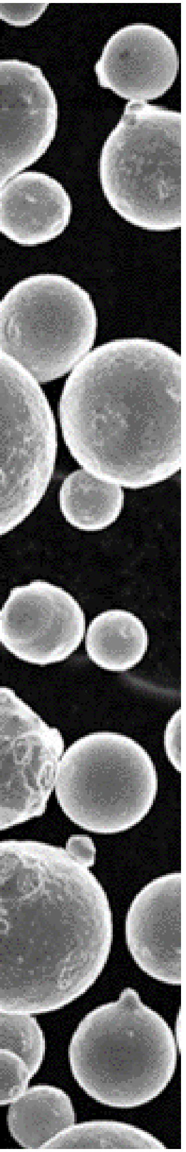
The purpose of an “engineering equivalence” approach

- **<u>To enable the material allowable and design value concepts in AM</u>**
- To enable a well-informed decision regarding the consistency of AM materials by leveraging all available information across a variety of metrics of engineering significance
  - Avoid fixating on strength alone as a determination of material equivalence
  - This is not a new concept, but as applied to AM, additional structure and standardization is needed
- To leverage the concept that material performance is derived from the relationship:

  Material → Process → Structure → Property → Performance

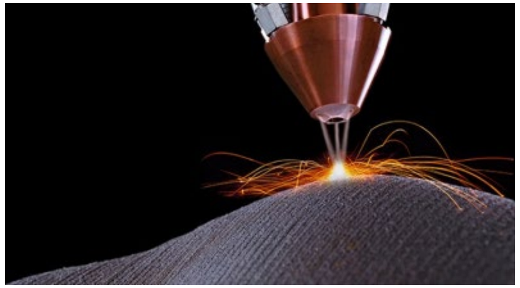
  - Equivalence does ***not*** generally mean “better than or equal to,” e.g., exceeds the specification minimum.
  - Equivalence implies fundamental characteristics and performance are “in-family” with a baseline set of data
  - Making determinations of what is, or is not, “in-family” generally requires engineering judgement
    - In many applications of engineering equivalence there are inadequate data for any one performance characteristic to establish true statistical confidence for equivalence of that particular characteristic
  - Engineering judgement is needed to keep the “false-call” rate and associated engineering review in balance.

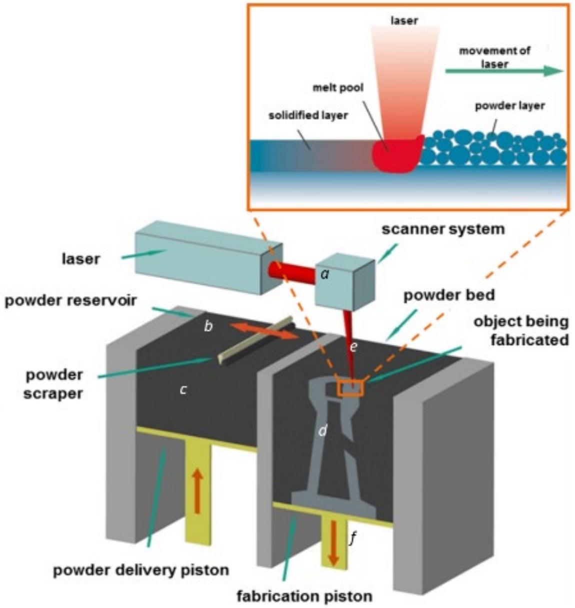
Prerequisites to Engineering Equivalence

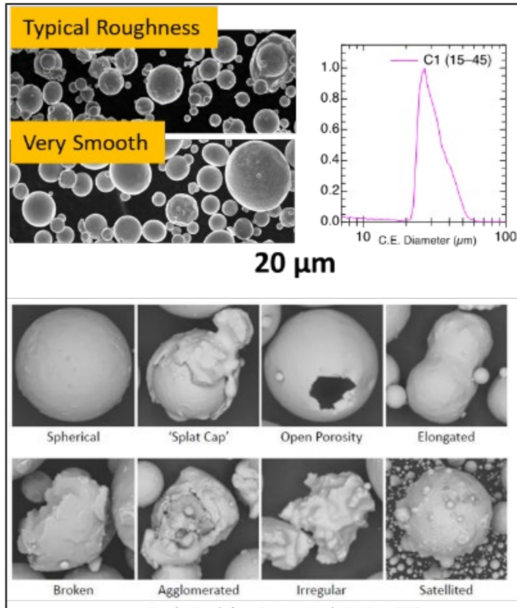


Similitude in feedstock and process

- The starting point for equivalence generally must be a reasonable match to the starting point that created the equivalence baseline
- Avoid expecting equivalence between apples and oranges
- Look for similitude in the following
  - Feedstock specification
    - Alloy chemistry
    - Feedstock production controls
    - Physical characteristics
    - Identical specification is best for similitude
  - Basic process definition and ***qualified processes***
    - LB-PBF under compatible conditions
    - DED under similar build conditions and scope
- Engineering equivalence may be possible across broader differences in starting points, but expect the depth of equivalence evaluation to be more exhaustive.





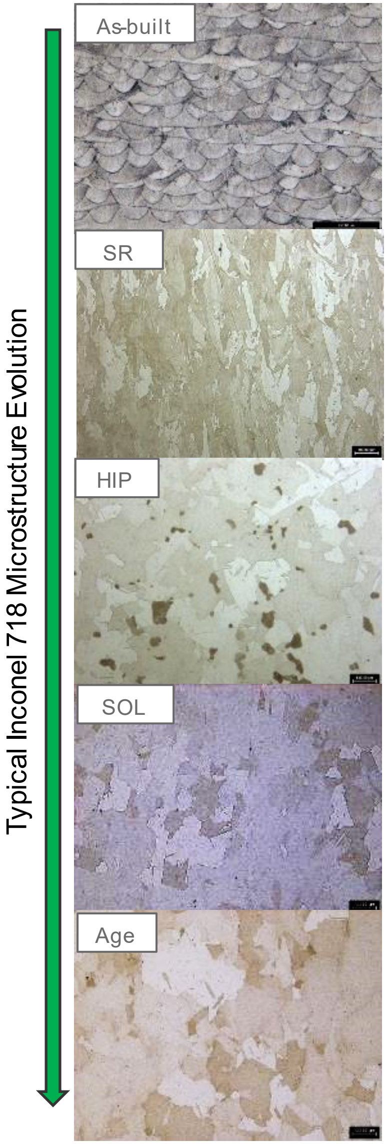


Powder Morphology. Courtesy Metal AM, Winter 2017.

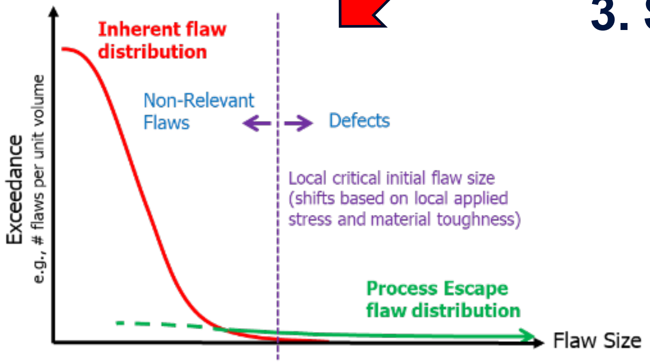
Engineering Equivalence Toolbox

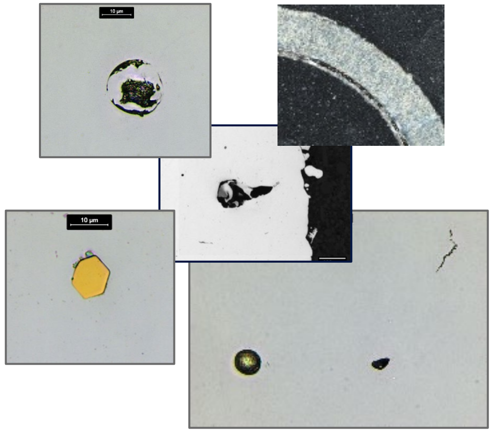
Engineering Equivalence Toolbox

1. Microstructure

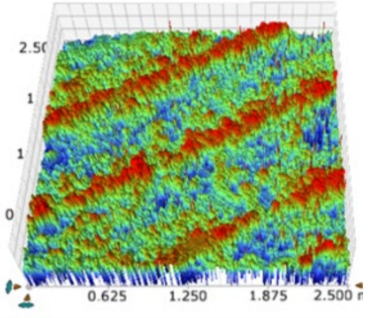


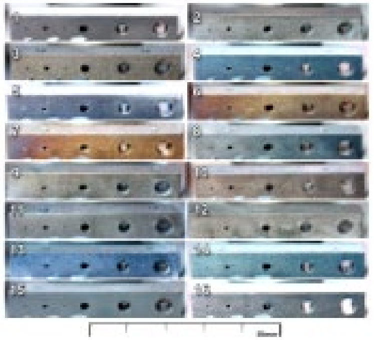
2. Flaw State



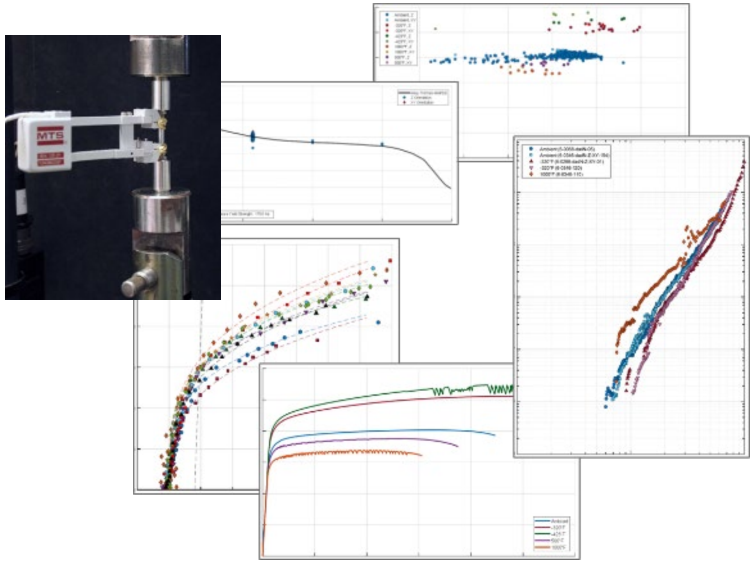


3. Surface Quality



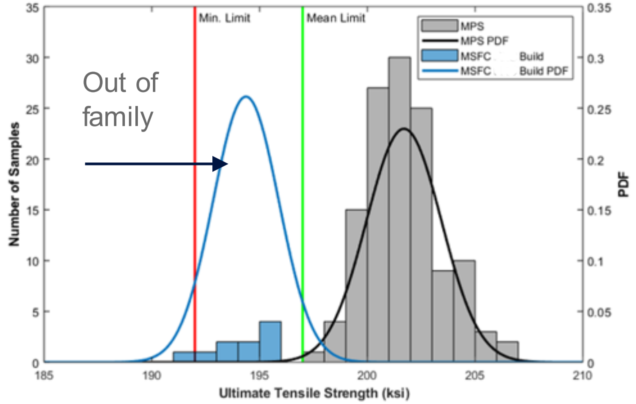


4. Mechanical Properties



5. Statistical Tools

In-family / out of family
“engineering assessments”

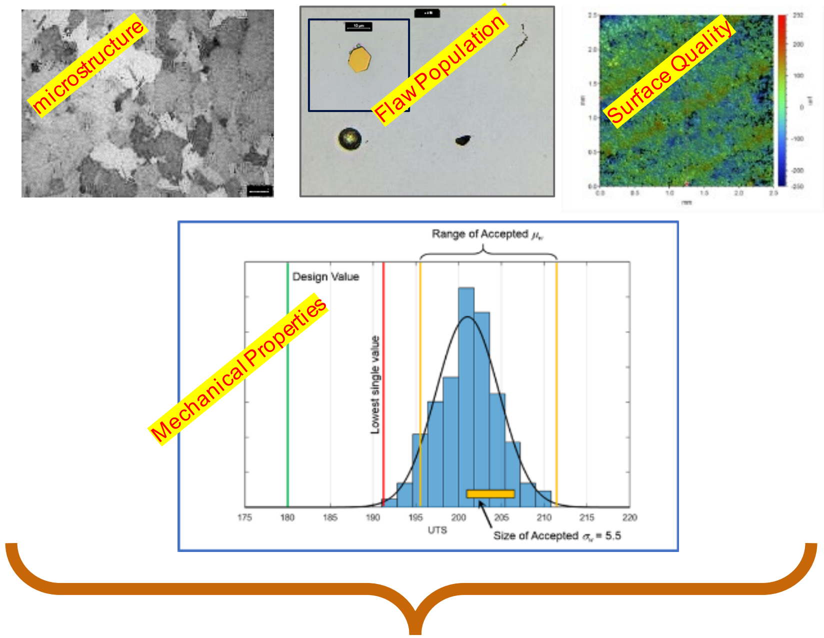


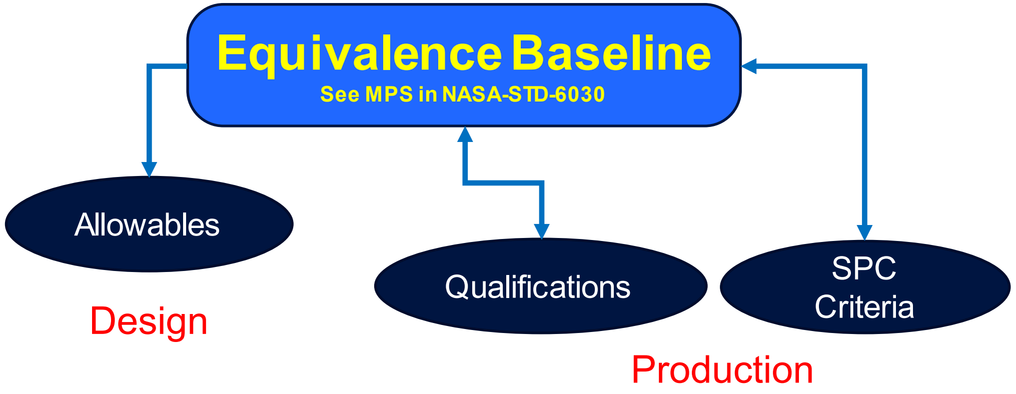
Baselines for Engineering Equivalence

Equivalent to what?

Equivalence Baselines

- Possession of a mature baseline for material equivalence is valuable and enabling for qualification and certification in AM
- Baselines mature with increasing quantities of data and should asymptotically converge on a consistent descriptor of the material
  - Definition of what range of material characteristics are "equivalent"
- Mature baselines:
  - Provide a basis for all the core tools of engineering equivalence evaluations
    - Microstructure, flaw population, surface quality, mechanical properties
  - Provide full descriptions and interpretive information for evaluation
  - Provide recommended evaluation metrics and acceptance criteria for a variety of end uses of equivalence: qualification, SPC, etc.

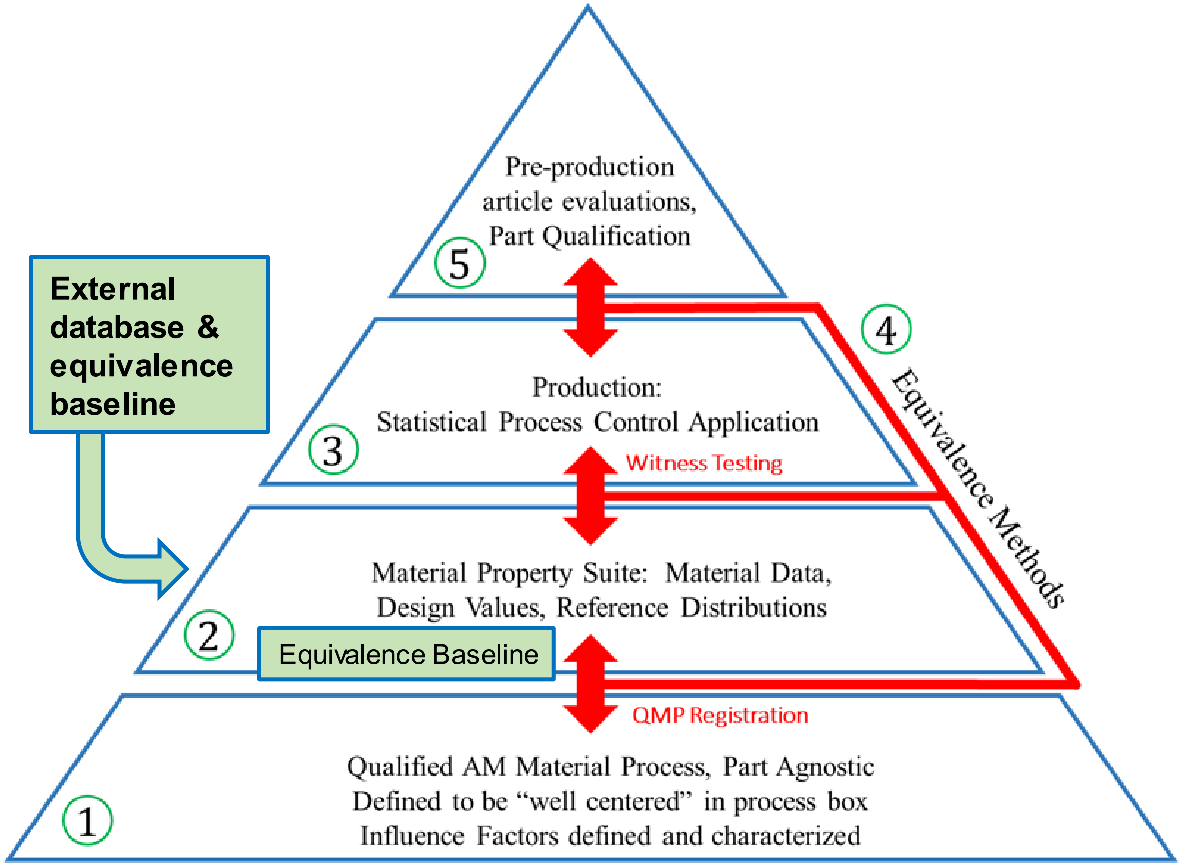




Applications of Engineering Equivalence

Scenarios for use of Engineering Equivalence

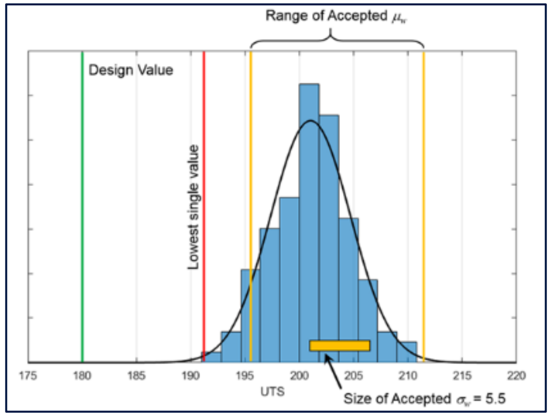
- Engineering equivalence evaluations enable the building block of AM material integrity
- The foundation of AM material control always starts with a qualified material process (see QMP, NASA-STD-6030)
- Data from qualified processes leads to the establishment of the equivalence baseline (property database)
- The equivalence baseline defines the targets for material engineering equivalence and provides:
  - A foundation for continued *process qualification and requalification*
  - A foundation for *build process witness test evaluation*
    - Ongoing *statistical process control*
  - A foundational role in *Part qualification* regarding material equivalence



Applications of Engineering Equivalence

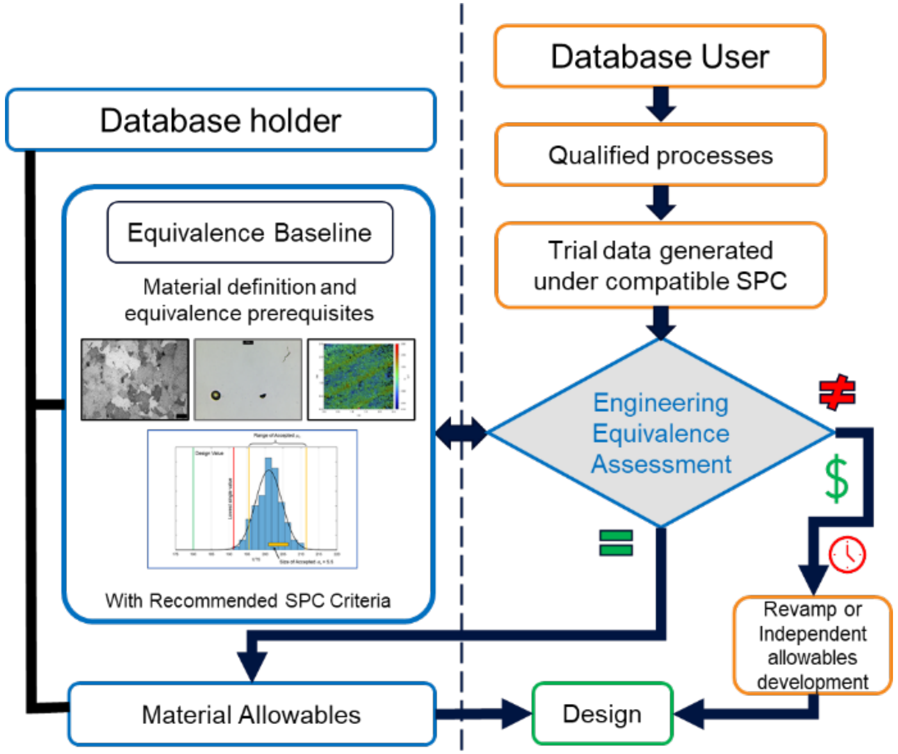
AM Build Acceptance (Witness)

See PCRD in NASA-STD-6030



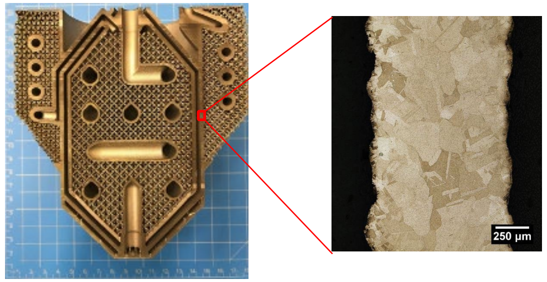
Engineering Equivalence Applications

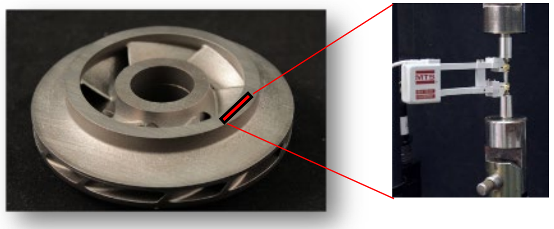
Databases for Material Allowables and Design Values



Part Qualification (PQ)

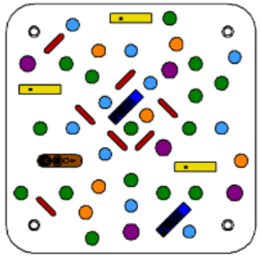
See Pre-production article evaluation and the QPP in NASA-STD-6030



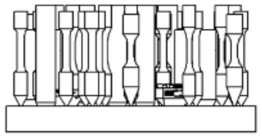


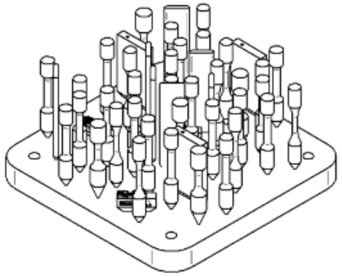
Machine/Process Qualification (IQ/OQ)

See Qualified Material Process, QMP, and QMP Registration in NASA-STD-6030



Specimen Type	Qty	Name	Key
High Cycle Fatigue	10	HCF-1 thru HCF-10	
Low Cycle Fatigue	5	LCF-1 thru LCF-5	
Tensile (RT)	15	TN-1 thru TN-15	
Tensile (Cryo, ET)	6	TN-16 thru TN-21	
Fracture Toughness	3	FT-1 thru FT-3	
Metallographic Samples	7	MET-1 thru MET-7	
Dimensional Samples	2	D-1 thru D-2	
Contour Analysis Samples	1	C-1	





Tools: (Always use all available tools for assessment)
Feedstock/process similitude, microstructure, flaw population, surface quality, mechanical properties, and statistical assessment

Summary and Conclusions

Engineering Equivalence as an enabler in AM

- There is more to AM alloys than bulk chemistry and tensile strength.
- Most AM alloys are exceedingly complex and require precise metallurgical control to meet engineering expectations against a variety of failure mechanisms that are often assumed to follow a specific alloy or alloy class based on precedent from traditional product forms:
  - Strength, ductility, fatigue, heat resistance, cryogenic ductility, toughness, tearing resistance, fatigue crack growth, stress rupture, hydrogen embrittlement, intergranular cracking, general corrosion, stress corrosion cracking, etc.
- Engineering equivalence is a methodology for evaluating the quality of AM materials that acknowledges the broad range of characteristics that must be assured for an alloy to meet its expectations.
- Like all alloys, AM material capability is derived from the “Process → Structure → Property → Performance” relationship
- Engineering equivalence is the enabler that allows the AM material ecosystem to remain healthy and self-consistent in the face of sensitive processes with a multitude of known and unknown failure modes.
- Maintaining engineering equivalence in AM materials when qualifying processes, qualifying parts, applying SPC, and accepting builds is the cornerstone of enabling the reliable use of material allowables and design values.
- Equivalence means “in-family.” ***Not*** “better than or equal to.”
- Balance is needed in the application of engineering equivalence to maintain the objectives and advantages of material engineering equivalence without an undue burden on operations.
- The devil is in the details: engineering equivalence is not an easy task - it requires reliable and diverse datasets, depth of knowledge in materials, good engineering judgement, and collaboration between engineering and quality assurance organizations.

Thank you.

Douglas.N.Wells@nasa.gov

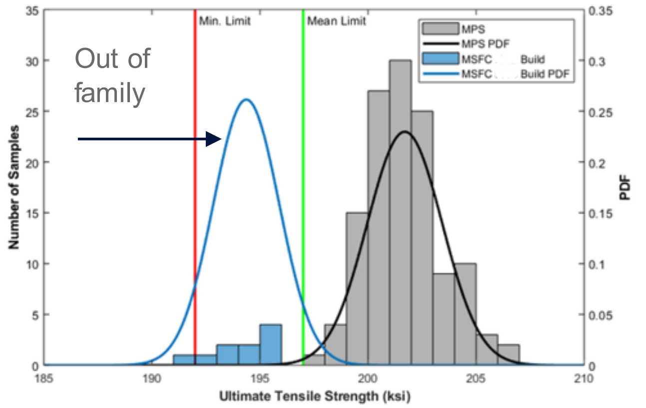
Back-up Content

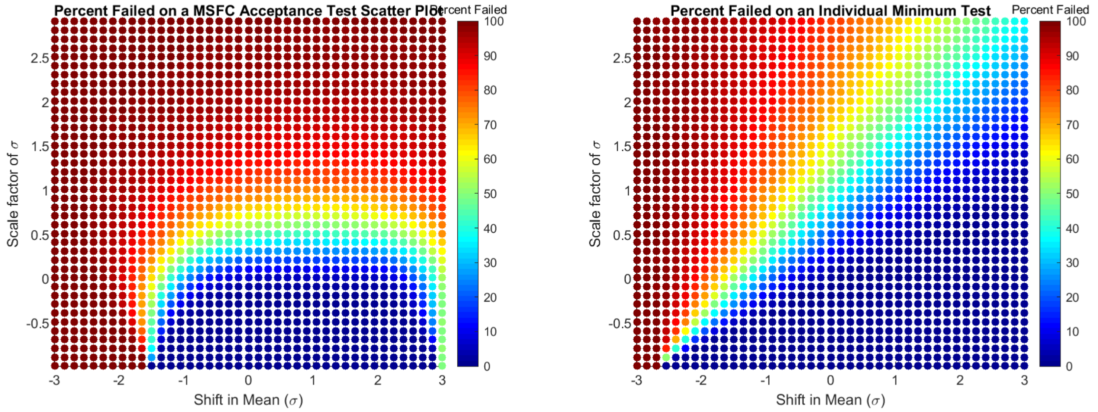
Engineering Equivalence Toolbox

Statistics

- Core part of the equivalence toolbox
- Most situations in AM needing equivalence evaluation do not have the luxury of sufficient data quantities for statistical determinations, *at a desired level of confidence*
  - Despite this, statistics as a tool is indispensable in equivalence
- Leverage stats for definitive determinations whenever feasible
- Use for insight and decision making in engineering equivalence
- Design of acceptance tests, control charts, "in-family" evaluations

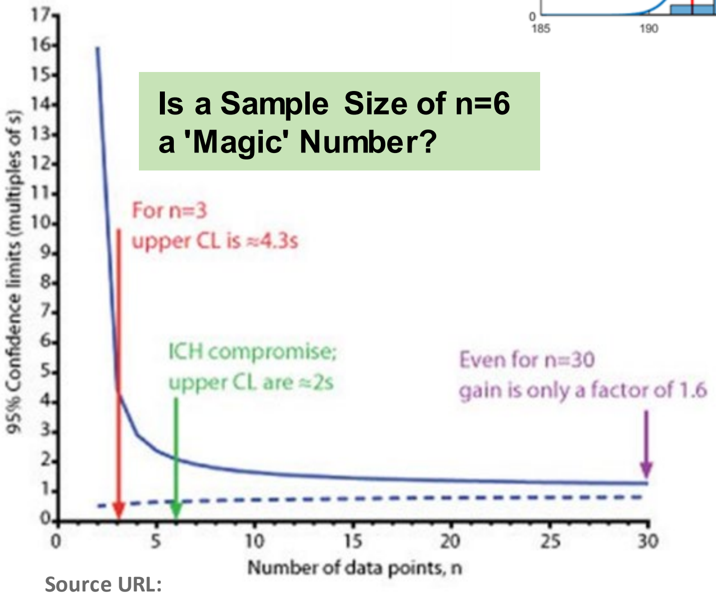
In-family / out of family "engineering assessments"





Monte Carlo simulations of acceptance test methodologies

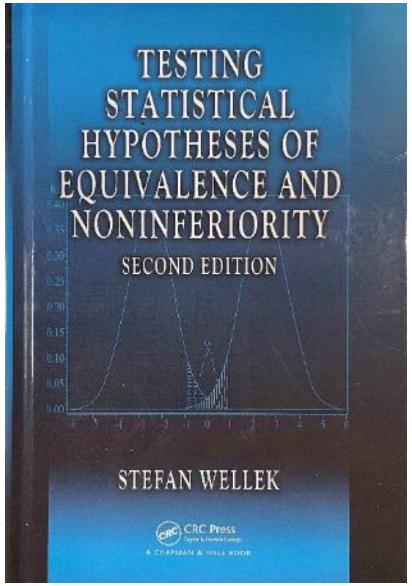
Is a Sample Size of n=6 a 'Magic' Number?



Source URL:

http://www.pharmtech.com/sample-size-n6-magic-number

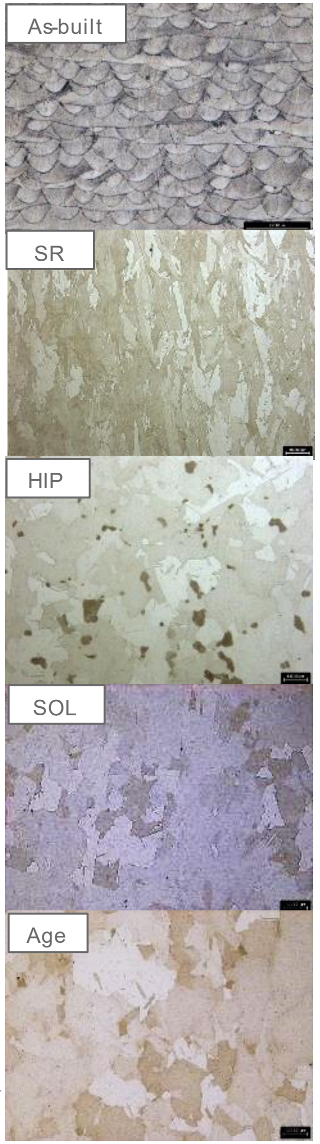
By Chris Burgess, PhD



The Deep End…

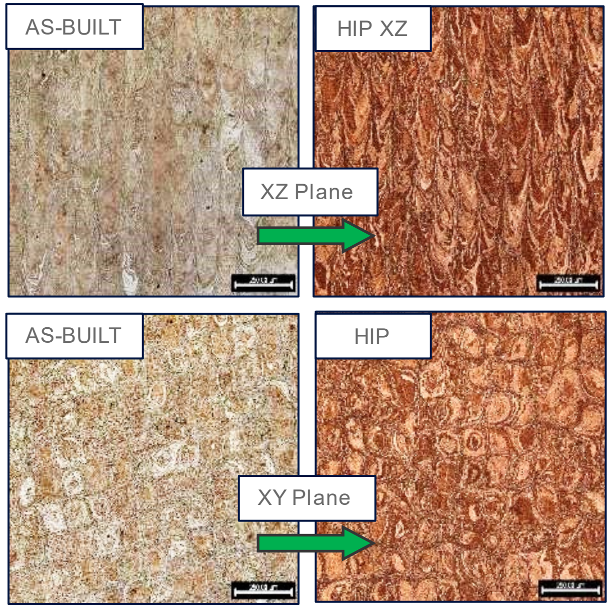
Engineering Equivalence Toolbox

Typical Inconel 718 Microstructure Evolution

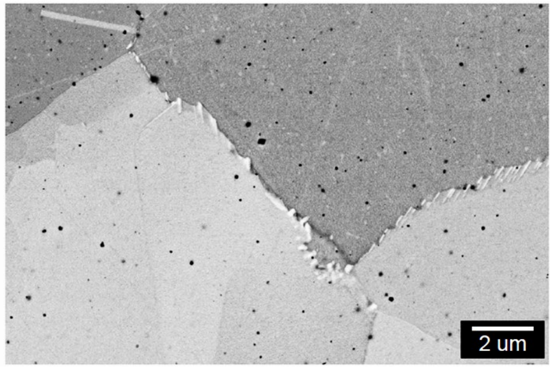


Microstructure

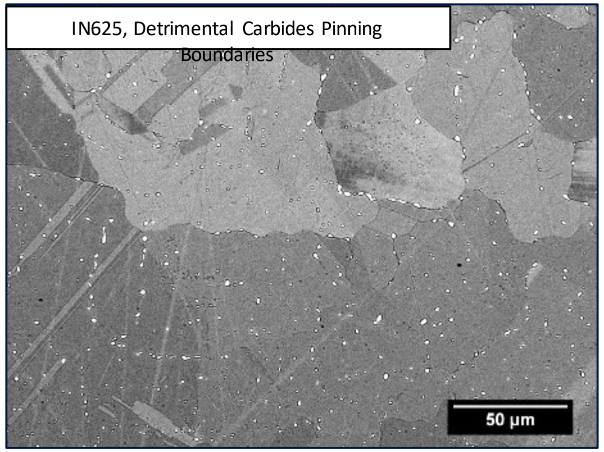
- Long term success in AM means understanding microstructure
- Material performance derives from microstructure, *particularly the details of performance*
  - E.g., corrosion or fatigue crack initiation are performance details not always well correlated to other properties
- Equivalence in microstructure can be difficult to quantify
  - Requires engineering judgement
- Understand the desired, or expected, microstructure
  - Define its core characteristics in the as-built and final forms
  - Phases, precipitates, recrystallization, grain size, grain shape, twinning, etc.
- Understand potential undesirable microstructures
  - Describe what the microstructure should NOT be



GR-COP42, Typical limited recrystallization



IN718 δ-phase at boundaries

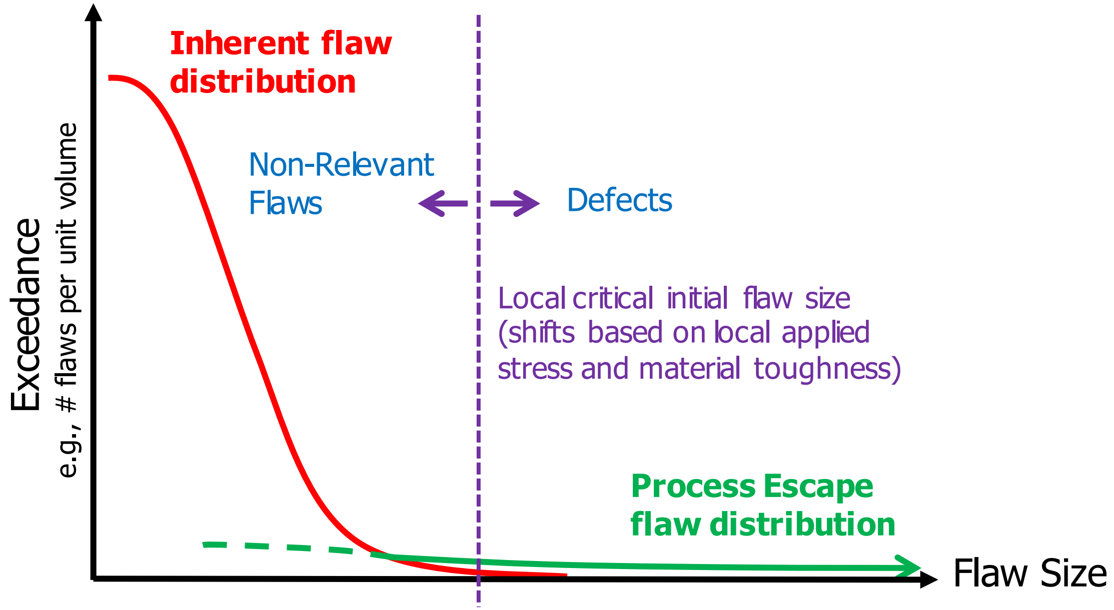


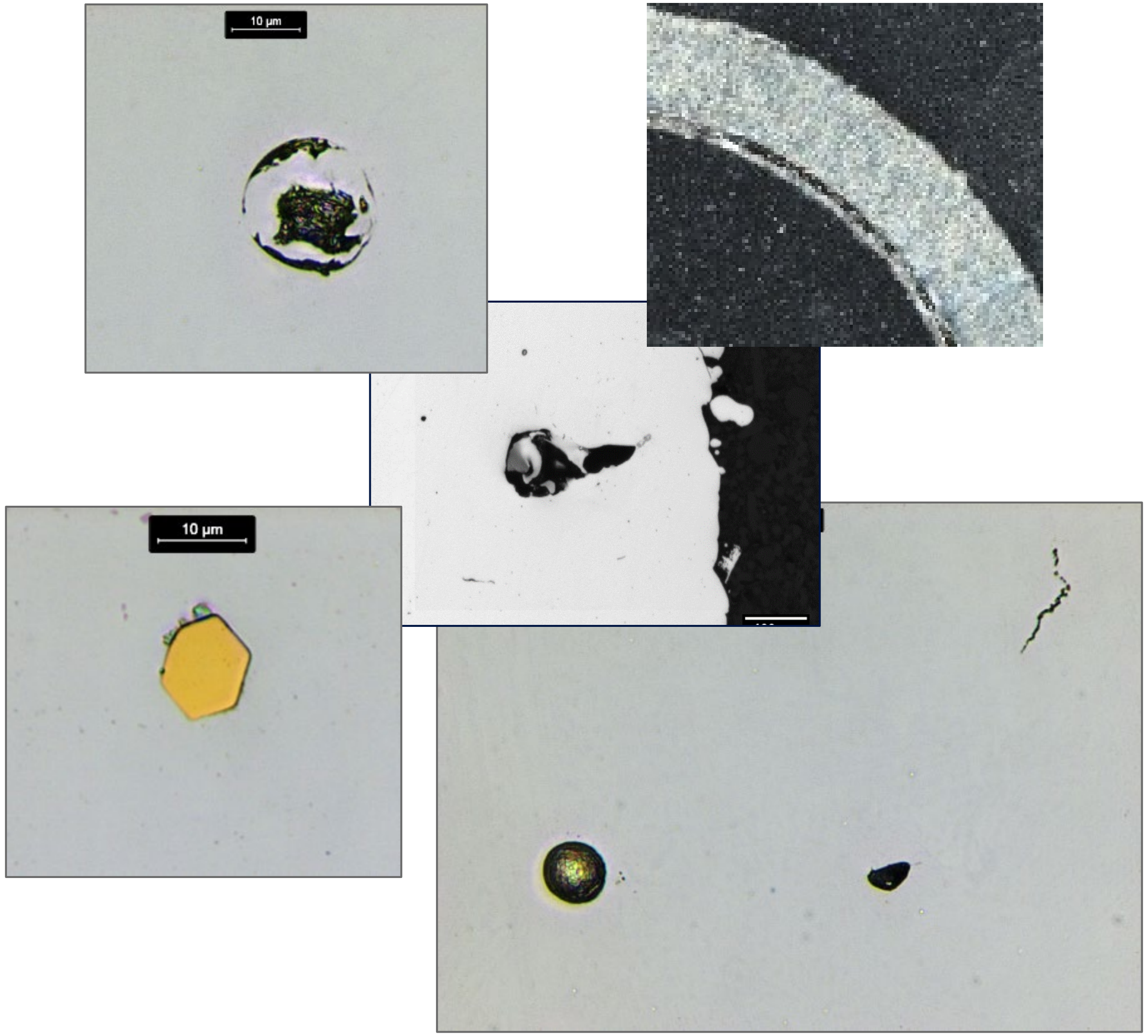
Undesired precipitates (carbides) on boundaries

Undesired lack of recrystallization in IN718

Flaw population

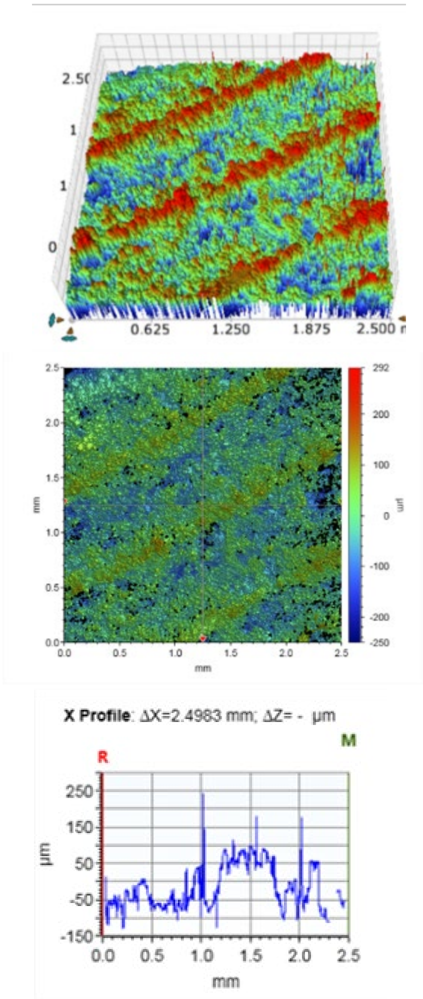
- In AM, the flaw population is a primary governor of material performance
- Quantifiable metrics are feasible to aid equivalency judgements for common inherent flaws — those flaws which are expected
  - Types, sizes, and frequencies of occurrence
- Equivalence in flaw population focuses on consistent material of intended quality — process escape flaws are not the focus here.





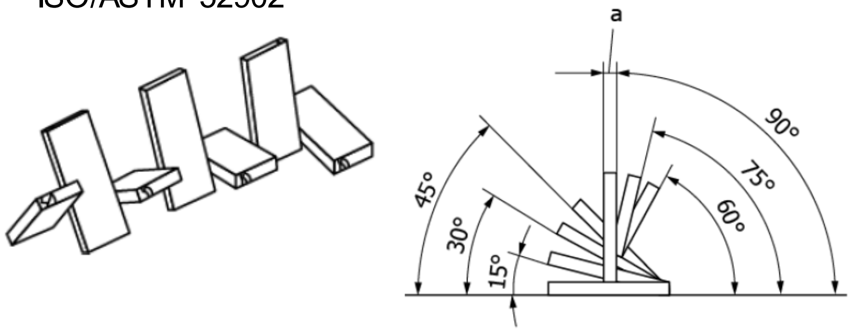
Engineering Equivalence Toolbox

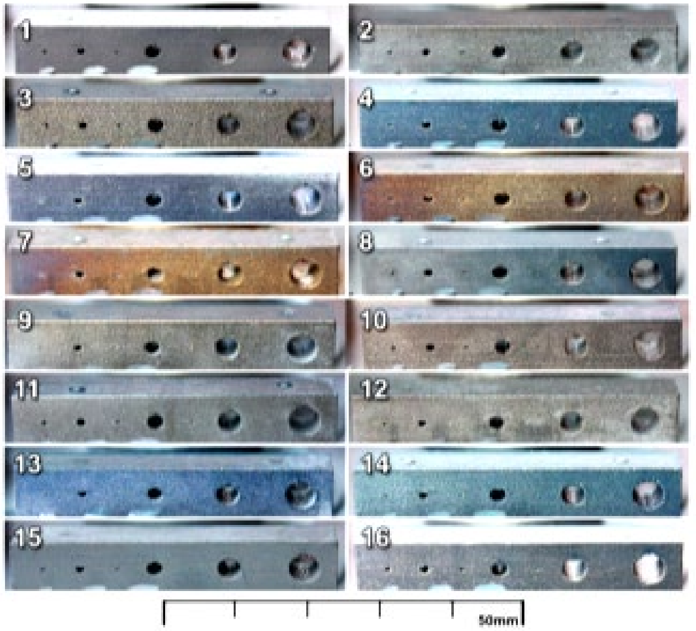
Surface Quality, Dimensional & Detail Resolution



- Evaluation of the surface quality, resolution of detail, and accuracy in dimensions can be important metrics when evaluating equivalency
- Surface quality may have direct influence on mechanical performance of AM materials when as-built surfaces remain
  - Fatigue life
  - Ductility
- Surface quality has numerous existing metrics defined, though their applicability to AM surfaces remains a topic of research
- Evaluations of equivalency regarding detail resolution can be difficult and subjective, not unlike microstructure comparisons
  - Brings "engineering judgement" to bear in engineering equivalency assessments

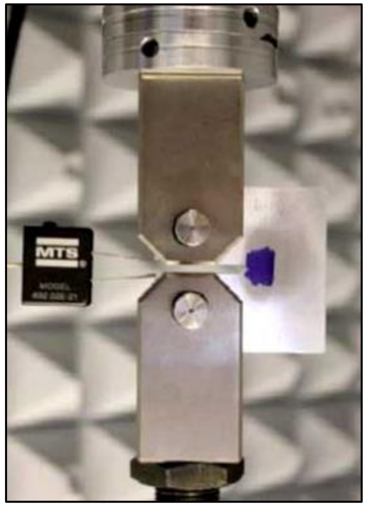
ISO/ASTM 52902





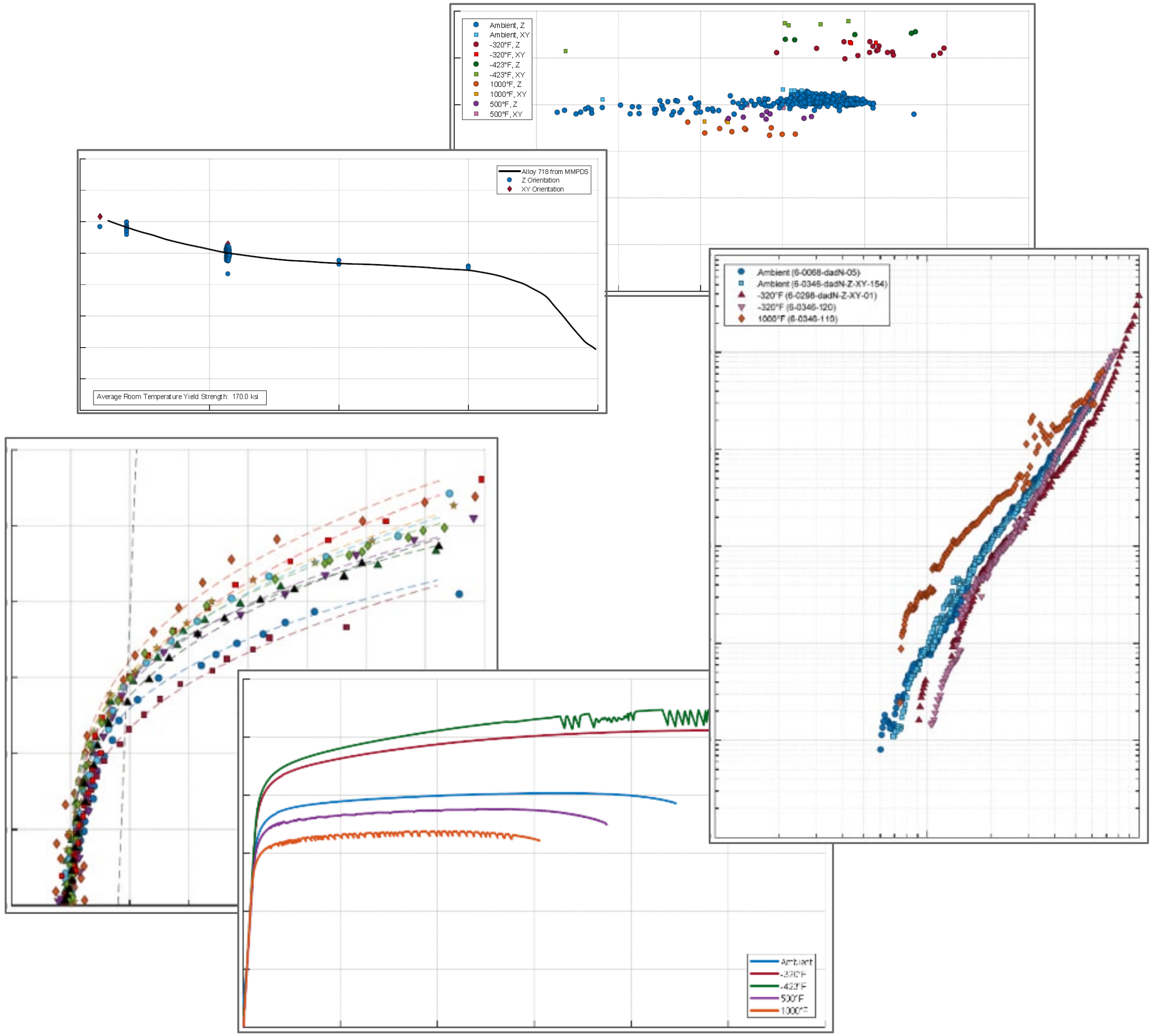
Gradl et al.,
Additive Manufacturing 47 (2021) 102305

Engineering Equivalence Toolbox



Mechanical Performance

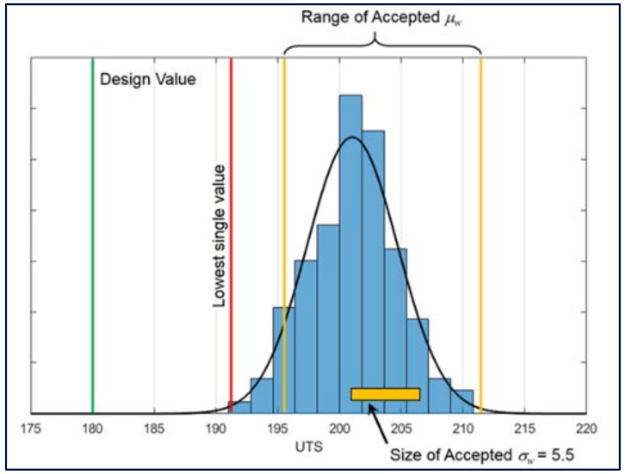
- Tensile strength is the predominant indicator of performance
  - Ultimate and yield strength
  - *Ductility* (elongation and reduction in area)
- Consider other failure mechanisms in the material system
  - Various failure mechanisms may show some correlation to each other, but actual material capability in each will be independent
    - Fatigue crack initiation
    - Toughness and tearing resistance
    - Fatigue crack growth rate
    - Special interest properties
      - Stress rupture
      - Temperature dependence
      - Environmental (HEE, SCC, SLC…)



Applications of Engineering Equivalence

AM Build Acceptance (Witness)

See PCRD in NASA-STD-6030



Objective:

Monitor consistency of material for production builds.

Why use Engineering Equivalence?

- Witness testing is the primary quantifiable metric used to monitor AM process quality.
- Witness testing acceptance through equivalence maintains the rationale for the applicability of material allowables and design values throughout production

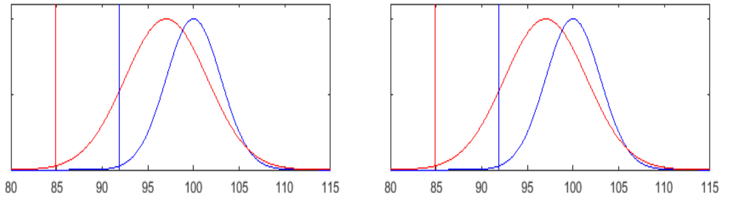
Tools: (somewhat limited, depth will be dependent on part classification)

- Evaluate across various metrics with enough data to do equivalence: microstructure, flaw population, tensile (4-6 specimens), fatigue, surface quality, special interest, etc.
- Leverage small sample statistics to the degree possible, see simulation on the right.
- Use statistics to monitor mean and variance :: control charts in continuous production

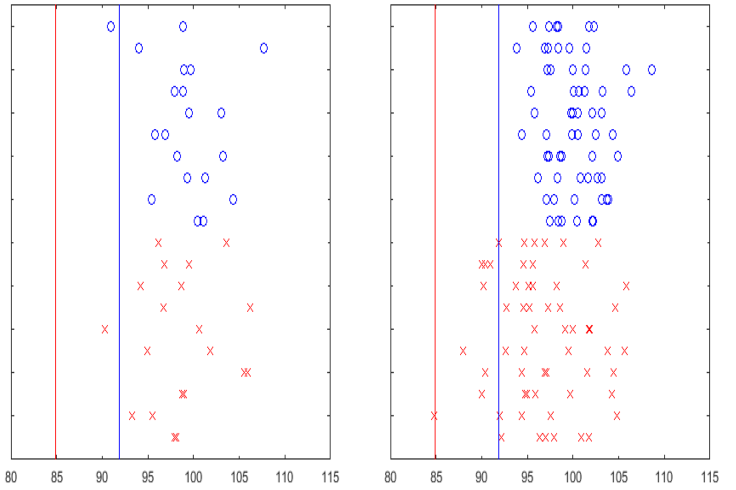
Equivalence Confidence:

Moderate, based on limited evaluations available across most tools, but robust for build acceptance.

Nominal process is blue, off-nominal in red



Two (2) witness tests per build | **Six (6) witness tests per build**



Process shift is hard to discern

Process shift discernable with analysis of mean and variation

Random draw from nominal and off-nominal process 10 times

Applications of Engineering Equivalence

Machine/Process Qualification (IQ/OQ)

See Qualified Material Process, QMP, and QMP Registration in NASA-STD-6030

Objective:

Demonstrate material quality from a specific machine under defined conditions is equivalent to past material used to set design properties.

Why use Engineering Equivalence?

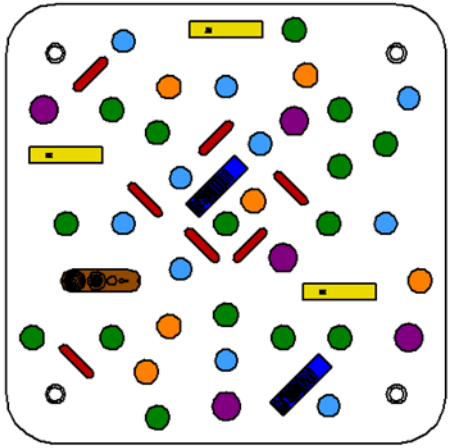
Re-occurring operation required of every AM machine. Testing quantities for high statistical confidence is generally impractical, or limited to a single attribute (e.g., tensile).

Tools: (use them all)

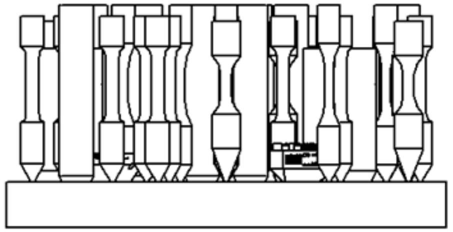
Feedstock similitude, microstructure, flaw population, surface quality, mechanical properties, statistical assessment

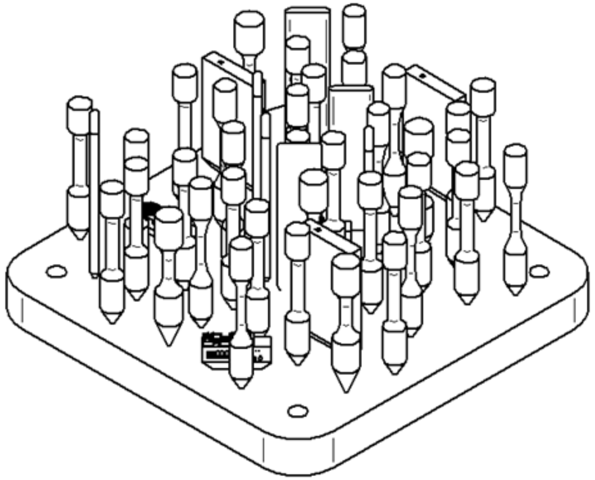
Equivalence Confidence:

Moderate to high, based on limited evaluations available across all tools.



Specimen Type	Qty	Name	Key
High Cycle Fatigue	10	HCF-1 thru HCF-10	
Low Cycle Fatigue	5	LCF-1 thru LCF-5	
Tensile (RT)	15	TN-1 thru TN-15	
Tensile (Cryo, ET)	6	TN-16 thru TN-21	
Fracture Toughness	3	FT-1 thru FT-3	
Metallographic Samples	7	MET-1 thru MET-7	
Dimensional Samples	2	D-1 thru D-2	
Contour Analysis Samples	1	C-1	





Applications of Engineering Equivalence

Part Qualification (PQ)

See Pre-production article evaluation and the QPP in NASA-STD-6030

Objective:

Substantiate within pragmatic limitations that the material quality throughout a new AM part is equivalent in the engineering sense to past material used to set design properties, i.e., substantiate specimen-to-part equivalence for applicability of allowables.

Why use Engineering Equivalence?

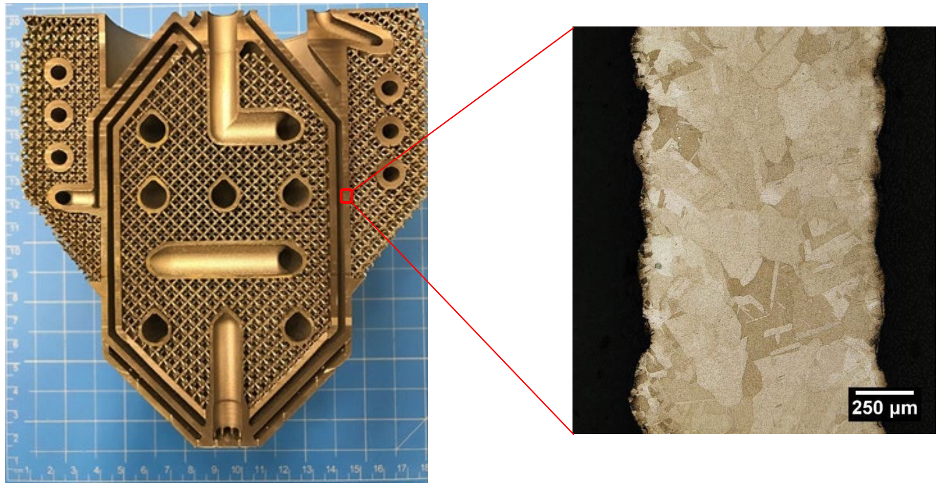
AM material quality within parts is likely to vary with geometry and build conditions. Evaluation of all properties directly is rarely feasible. Require internal quality and mechanical properties to be in family with the equivalence baseline. Engineering judgement is likely required.

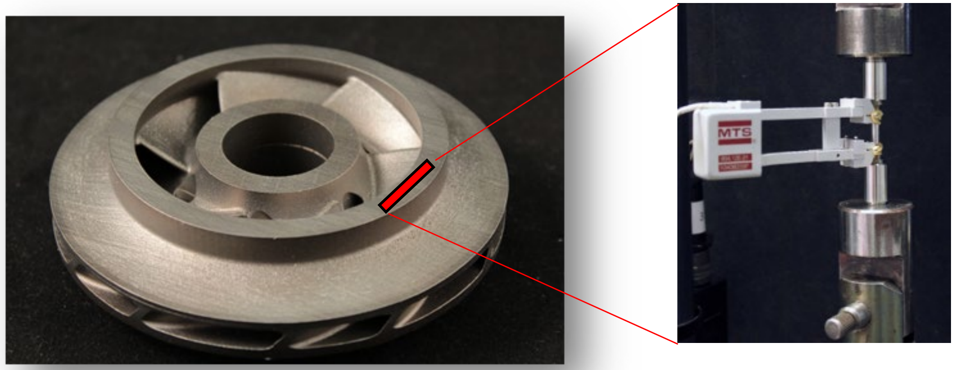
Tools: (use all available, may be limited)

Feedstock similitude, *microstructure & flaw population (always)*, surface quality, mechanical properties (as available, even if sub-scale), statistical assessment (usually limited)

Equivalence Confidence:

Moderate, based on limited evaluations available across tools, but an indispensable aspect of part qualification.





Applications of Engineering Equivalence

Material Allowable and Design Value Databases

Objective:

Leverage pre-existing AM material databases for material allowables and design values to reduce cost.

Why use Engineering Equivalence?

Equivalence evaluations will be less expensive than full characterization. Similitude across numerous metrics between baseline and trial data reduces the risk of unforeseen failure modes in the trial material and provides confidence trial material will meet expectations of the alloy.

Tools: (use all available)

Feedstock/process similitude, microstructure, flaw population, surface quality, mechanical properties, statistical assessment (usually moderately robust)

Equivalence Confidence:

High, based on evaluations available across all tools. Evaluations generally will have tangible statistical significance in sample quantity and lot variability.